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Research and Development Report

INSTRUMENTED IMPACT TESTING OF FABRIC-REINFORCED COMPOSITE MATERIALS

by

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Instrumented impact and ultrasonic inspection were used to assess the impact damage resistance of six fabric-reinforced laminates. Polyester and vinylester resins reinforced with woven roving, biaxial reinforcment, and glass/Kevlar hybrid were evaluated. Biaxial fabric reinforced resins had the best impact resistance. This determination is based on the ability of these materials to survive impact with the lowest friction of impact energy resulting in damage. In addition, laminates with biaxial reinforcement had comparable damage areas to the other materials.

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ABBREVIATIONS

BR - biaxial reinforcement
cc - cubic centimeters
CoNap - Cobalt Napthenate
GK - glass/Kevlar
g/sq.m - grams per square meter
in. - inches
lbs. - pounds
MEKP - methyl ethyl ketone peroxide
MHz. - megahertz
oz. - ounces
PE - polyester
sq. - square
VE - vinyl ester
WR - woven roving
wt. - weight

ABSTRACT

Instrumented impact and ultrasonic inspection were used to assess the impact damage resistance of six fabric-reinforced laminates. Polyester and vinylester resins reinforced with woven roving, biaxial reinforcement, and glass/Kevlar hybrid were evaluated. Biaxial fabric reinforced resins had the best impact resistance. This determination is based on the ability of these materials to survive impact with the lowest fraction of impact energy resulting in damage. In addition, laminates with biaxial reinforcement had comparable damage areas to the other materials.

ADMINISTRATIVE INFORMATION

This study was supported by the Naval Oceanographic Office and administered by Craig Willett (Code PHE) under DTRC Work Unit 1-2802-104.

INTRODUCTION

The impact damage resistance of six fabric-reinforced composites was assessed with instrumented impact testing. The materials were composed of three different classes of fabric with polyester and vinylester matrices. The fabrics were E-glass woven roving, weft-knitted biaxial E-glass, and an E-glass/Kevlar* hybrid.

The six laminates evaluated are a representative cross-section of the composite materials which are appropriate for small boat hulls. For the last four decades, the reinforcement of choice for small boat hulls has been E-glass woven roving (1). Recent developments in fabrics include the biaxial fabric and

* Use of manufacturers tradename does not constitute endorsement, either expressed or implied, by DTRC.

glass/Kevlar hybrid evaluated in this study. In both cases, the advantage of the new materials over woven roving is an increase in flexural stiffness and strength (2), which results in a weight reduction of the structure when it is designed for comparable mechanical properties. One concern with these new material systems, in particular with the biaxial fabric, is the ability of the material to contain impact damage. In a recent study comparing the impact resistance of woven vs. biaxial reinforcement, no decrease in impact resistance was observed for the biaxial reinforced materials (3). In that study, dropped ball impact was used in conjunction with C-scan damage area to assess the impact resistance. In the present study, instrumented impact and C-scan damage area were used to determine the relative impact resistance of the various potential hull materials. With instrumented impact (4), the material response to the impact event is characterized by force-time and energy-time curves, which are calculated from tup force response.

MATERIALS

Six composite laminates were received from Harbour Marine Services, (Mississauga, Ontario, Canada). The composites were fabricated by hand lay-up into 38 in. x 38 in. panels, which were then trimmed to 3 ft. x 3 ft. A summary of the materials and their composition follows.

Woven Roving/Polyester (WR/PE)

- One layer of 1.5 oz. mat, Fiberglass Canada #M751 (450g/sq.m)
- Two layers of woven roving/mat reinforcement, Fiberglass Canada #18.10.
- Polyester resin, Fiberglass Canada #44-119
  Catalyst: 20 cc MEKP/2 liters resin

Woven Roving/Vinylester (WR/VE)

- One layer of 1.5 oz. mat, Fiberglass Canada #M751 (450g/sq.m)
- Two layers of woven roving/mat reinforcement, Fiberglass Canada #18.10
- Vinylester resin, Dow Chemical Derakane #510-A-40
  Catalyst: 1.25% MEKP
  Promoter: 0.3% CoNap
  Accelerator: 0.1% Dimethylaniline

Biaxial Reinforcement/Polyester (BR/PE)

- One layer of 1 oz. mat, Fiberglass Canada #M751 (300 g/sq.m)
- Five layers of 18 oz. biaxial reinforcement, Fiberglass Canada #8518
- Polyester resin, Fiberglass Canada #44-119
  Catalyst: 20 cc MEKP/2 liters resin

Biaxial Reinforcement/Vinylester (BR/VE)

- One layer of 1 oz. mat, Fiberglass Canada #M751 (300g/sq.m)
- Five layers of 18 oz. biaxial reinforcement, Fiberglass Canada #8518
- Vinylester resin, Dow Chemical Derakane #510-A-40
  Catalyst: 1.25% MEKP
  Promoter: 0.3% CoNap
  Accelerator: 0.1% Dimethylaniline

Glass-Kevlar Hybrid/Polyester (GK/PE)

- One layer 1.5 oz. mat, Fiberglass Canada #M751 (450 g/sq.m)
- Two layers C72K/200 glass-Kevlar hybrid
- Catalyst: 15cc MEKP/2 liters resin

Glass-Kevlar Hybrid/Vinylester (GK/VE)

- One layer 1.5 oz. mat, Fiberglass Canada #M751 (450 g/sq.m)
- Two layers C72K/200 glass-Kevlar hybrid
- Catalyst: 1.0% MEKP

The characteristics of the panels were determined by Harbour Marine Services, and are recorded in Table 1. Apparently incineration was used to determine glass percent. In the glass/Kevlar hybrid panels, the Kevlar was incinerated along with the resin, so the resin weight percent is actually the combined weight percent of Kevlar and resin.

Examples of the three reinforcements are shown in figure 1. The woven roving is a plain weave backed by a mat. The biaxial reinforcements are distinguished by flat, uncrimped rovings, with a warp and a weft ply stitched together to compose one layer of fabric. The composition of the glass/Kevlar hybrid, DuPont's Aramat 72K/200, is given in Table 2.

PROCEDURE

Several 4 in. x 6 in. test samples were machined from the laminates. The approach was to non-destructively inspect each sample ultrasonically and record the C-scan, subject the panel to a low velocity impact, and then record the C-scan of the damaged sample. The impact testing was accomplished with a Dynatup Model 8200 drop tower (Figure 2). Samples were held in a Boeing 7260 support fixture (Figure 3), in which the samples are clamped at four locations over a 3 in. x 5 in. opening.

The instrumented tup can be fitted with hemispherical inserts of various diameters. Two inserts, 0.5 and 1.0 inch in diameter, were chosen for this study. In the initial set of experiments, three samples from each laminate were impacted with the 0.5 inch tup and three with the 1.0 inch tup. Since the

thickness of the samples varied from composite to composite, the levels of impact were normalized to the sample thickness. For the 0.5 inch tup impacts, the impact levels chosen were 1000, 1500, and 2000 in.lbs./in. thickness. For the 1.0 inch tup impacts, the levels were 1500, 2000, and 2500 in.lbs./in.

Fabric-reinforced composites typically will contain impact damage to the region of sample circumscribed by the contours of the impacting surface. Therefore, as the tup diameter increases, the laminates can sustain higher levels of impact without penetration. In this initial set of experiments, the levels were chosen such that there were no penetrations of the tup through the sample.

In Table 3, the impact energy level (in.lbs./in.), the impact energy (in.lbs.), the drop height (in.), and the average panel thickness (in.) are recorded for the 0.5 inch tup impacts. The impact weight was 15.1 lbs. In Table 4, these values are given for the 1.0 inch diameter tup impacts, in which the impact weight was 15.4 lbs.

Because of the limited nature of the program, only one sample of each material was impacted at a given energy level. This is considered adequate, however, since the energy-time and force-time curves generated from the instrumented drop tower have been shown to be reproducible (5).

NONDESTRUCTIVE INSPECTION

The machined samples were inspected with an ultrasonic scan system, FLAWMASTER 2000 SA, manufactured by the J.B. Engineering and Sales Co., Inc. A 2.5 inch focussed 5 MHz transducer with a diameter of 0.75 inches was used as both the transducer and receiver. The tests were carried out in the pulse echo mode of operation.

In order to determine the proper sensitivity level for each of the material systems inspected, one specimen of each material system was scanned ultrasonically. The transducer was focused on the midplane of the material and the attenuation level from the backwall signal was monitored. During this preliminary inspection, the threshold attenuation level was varied until the entire panel was above the threshold limit, although minor areas of higher attenuation were allowed. An attenuation of 45% of the backwall signal was determined to be an appropriate threshold setting for all the material systems tested.

In this test program, each sample was scanned prior to and immediately after the impact. Therefore, the post-impact inspection was performed using the same settings that were used for the pre-impact inspection. This procedure eliminates any possibility of recording signals indicative of damage which are not actual material discontinuities caused by the impact event.

RESULTS AND DISCUSSION

IMPACT TESTING

It is our assumption that the energy of impact is either stored elastically in the material during the event, or it causes some form of damage. It is not a given that, for application as structural material in small boat hulls, the material with the best impact resistance characteristics is one which minimizes the fraction of energy which causes damage. For small boat hulls it is desirable that damage from the inevitable impacts be contained to the impact site so that repair can be facilitated (6). At constant damage area, however, it would seem desirable to minimize the fraction of energy lost to damage formation and growth, that is, to maximize the fraction of energy stored elastically.

The possibility of large impact damage areas is the reason for concern over the use of biaxial fabric. It is generally thought that the impact response of biaxial fabric reinforced composites would be similar to the response of laminated tape composites to impact, which in general causes delaminations to spread well away from the impact site. However, the results from an earlier investigation at this Center using dropped ball impact and C-scan damage area showed that biaxial fabric reinforced composites contained damage as well as woven roving reinforced materials (3).

Energy-Time Behavior

The conclusions of the earlier study have been confirmed herein, with the data from the instrumented drop tower providing insight to the acceptable impact response of biaxial fabric reinforced composites. In Figures 4-6, Energy-Time curves of WR/PE, BR/PE, and GK/PE are shown at the 1000, 1500, 2000 in.lbs./in. level, respectively. In Figures 7-9, the energy responses are shown for WR/VE, BR/VE, and GK/VE at the same impact levels. All the impacts from which Figures 4-9 were generated used the 0.5 inch diameter tup. The difference between the maximum energy and the energy at the end of the test is the amount of energy which did not result in damage, and this value is significantly larger for BR/PE and BR/VE. Thus impact event produces less damage in the biaxial fabric reinforced materials, BR/PE and BR/VE, than in woven roving and glass/Kevlar hybrid reinforced composites; i.e., more energy is elastically stored by BR/PE and BR/VE. This pattern of behavior was also followed at all energy levels with the 1.0 inch tup diameter impacts, as shown in Figures 10-15. The superior ability of the biaxial fabric reinforced materials to absorb impact energy elastically becomes more evident as the impact level increases, particularly for the polyester resin composites (see Figure 12).

The superior ability of the biaxial fabric to store impact energy elastically, rather than form damage, is better illustrated in figures 16 and 17. In these figures, the fraction of energy stored elastically, (Emax-Emin)/(Emax), is plotted

against impact energy level. Not only does the biaxial fabric store more energy elastically than woven roving and the glass/Kevlar hybrid, the stored energy fraction degrades less rapidly with increasing energy level than the other materials. The stored energy parameters for all 36 impacts performed in this study have been collected in Table 5.

The glass/Kevlar hybrid reinforced materials, GK/PE and GK/VE, were comparable to woven roving systems in response to low velocity impact. If there is an advantage in using glass/Kevlar hybrid reinforcement (over woven roving) in small boat hulls, it would be in higher specific static mechanical properties, but not in impact resistance.

Force-Time Behavior

The force-time curves are less instructive than the energy-time behavior, but they do offer information that verifies conclusions made from the energy plots. Figure 18 is the force-time response of WR/VE, BR/VE, and GK/VE impacted with the 0.5 inch diameter tup at 1000 in.lbs./in. Figure 19 shows the behavior at 1500 in.lbs./in., and Figure 20 at 2000 in.lbs./in. Damage results in less ability to carry load and thus causes load drops. BR/VE curves are the smoothest, indicating that the least damage formed in this material.

There are two kinds of load drop. One has the appearance of noise, with a magnitude from 10-100 lbs, and the second is a much larger drop of several hundred pounds and occurs at about 0.004 to 0.005 seconds after impact. This second type, which did not

occur in biaxial fabric reinforced material, can be seen in Figures 19 and 20 for WR/VE and GK/VE. It is outside the scope of this study to determine the modes of damage which cause these two observed material responses, although it can be said that the "noisier" the force response, the larger the amount of resulting damage.

DAMAGE AREA

As mentioned, it is probably only desirable to have a material which maximizes the stored energy parameter if this material also contains the impact damage, i.e., the impact does not result in large delaminations. Damage area determination from ultrasonic inspection have confirmed the conclusions of an earlier study (3), which showed no tendency of biaxial fabric reinforced composites to form large planar delaminations which extend to areas much larger than the impactor diameter.

In Figure 21, the C-scans are shown for WR/PE after impact with the 1.0 inch diameter tup at 1500, 2500, and 3500 in.lbs./in. energy levels. The C-scans for BR/VE at the same levels are shown in Figure 22 and for GK/VE in Figure 23. The data indicate that the three materials tested have comparable ability to contain damage to the impact site.

All six material systems tested are translucent, and it is clear from visual inspection that impact damage areas are not significantly different. It should be noted that in biaxial fabric reinforced composites, impact causes a separation between the warp and weft plys of the last layer, particularly at the

higher impact levels. In Figures 24, 25, and 26, backface damage of all six materials are shown after impact with the 0.5 inch diameter tup at the three energy levels. The rovings which separate from the laminate in the biaxial fabric materials, as seen in Figure 25, only occurs in the last layer and appears superficial. Internal damage is confined to the roughly circular area in the center of the sample, as evidenced by the C-scans in Figure 22.

PENETRATION STUDY

A brief investigation was made to determine the maximum impact level the polyester matrix composites could sustain without penetration by the 0.5 inch diameter tup. All materials withstood the 2000 in.lbs./in. level without penetration in the first set of tests.

The level selected for the penetration was 2500 in.lbs./in. When a GK/PE sample was impacted at this level, the tup penetrated. The energy level was reduced to 2250 in.lbs./in., but the tup also penetrated at this level. The level was reduced to 2100 in.lbs./in, and the tup again penetrated. The maximum energy level that glass/Kevlar hybrid reinforced polyester can withstand (with the 0.5 inch diameter tup) is approximately 2000 in.lbs./in.

The process of searching for the impact level necessary for penetration was repeated for woven roving/polyester and biaxial reinforcement/polyester. WR/PE was not penetrated at 2100 in.lbs./in., but was penetrated at 2250 in.lbs./in. BR/PE

required much higher levels of impact before penetration. It was found that 3500 in.lbs./in. was necessary for penetration through BR/PE. The damage in the BR/PE sample penetrated was still contained to the impact site, except the characteristic separations of tow in the last ply.

SUMMARY AND CONCLUSIONS

1. The impact resistance of woven roving, biaxial fabric, and a glass/Kevlar hybrid fabric reinforced polyester and vinylester resins was assessed with instrumented impact and ultrasonic inspection.

2. Of the six materials tested, the two composed of biaxial reinforcement had superior impact resistance. This determination is based on ability to store impact energy elastically.

3. Ultrasonic inspection showed that all six materials tested had comparable C-scan damage areas at a given impact energy level.

4. Glass/Kevlar hybrid reinforced materials appear to offer no advantage in resistance to low velocity impact compared with a non-hybrid E-glass reinforced system.

5. An analysis parameter has been introduced which yields information about impact resistance of composites. It is the stored elastic energy parameter, defined as (Emax-Emin)/Emax, which is the fraction of impact energy that did not result in

damage. Impact resistance increases with the value of this parameter, and it is instructive to plot the stored elastic energy as a function of impact level.

6. Biaxial fabric reinforced composites had the highest value of stored elastic energy parameter and the best retention of the value with increasing energy level.

7. The minimum energy levels required for penetration with the .5 inch diameter tup were 2100 in.lbs./in. for glass-Kevlar/polyester, 2250 in.lbs./in. for woven roving/polyester, and 3500 in.lbs./in. for biaxial reinforcement/polyester.

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2. NSCSES, private communication.

3. T. Juska, R.M. Crane. and E.T. Camponeschi, "Impact Damage Resistance of Candidate Materials for the HSL Hull Structure", DTRC-SME-89/40.

4. R.M. Crane and T.D. Juska, "Instrumented Impact Testing of Composite Materials", DTRC-SME-88/73, January 1989.

5. R.M. Crane and T. Juska, unpublished data.

6. T. Clements, Harbour Marine Services, Mississauga, Ontario, Canada, personal communication.

Table 1. Characteristics of the panels as determined by Harbour Marine Services. All weights are in pounds, and percentages are weight percent.

Description	WR/PE	WR/VE	BR/PE	BR/VE	GK/PE	GK/VE
Glass wt.	5.75	5.75	7.12	7.12	4.50	4.50
Total wt.	11.87	12.87	12.25	12.87	10.12	11.25
Resin wt.	6.12	7.12	5.12	5.75	5.62	6.75
Resin %	51.6	55.3	41.8	44.7	55.5	60.0
Glass %	48.4	44.7	58.2	55.3	44.5	40.0
Panel wt.	10.5	11.2	10.7	11.5	8.75	9.62
lbs/sq.ft	1.17	1.25	1.19	1.28	0.97	1.07
Thick (in.)	0.136	0.134	0.154	0.156	0.116	0.121

Table 2. Composition of the glass/Kevlar hybrid, DuPont's Aramat 72K/200.

Component	G/SQ.M	OZ/SQ.YD	Wt. % In Base Fabric	Wt % in Total Fabric
Glass Fiber	245.6	7.2	63	41.1
Kevlar 49	144.0	4.2	37	24.0
Mat Backing	200.0	5.9	--	33.5
Stitching Yarn	8.0	0.2	--	1.4
Total	597.6	17.5		

TABLE 3. Impact energy level (in.lbs./in.), energy (in.lbs.), drop height (in.), and panel thickness (in.) for the impacts with the 0.5 in. diameter tup. The drop weight was 15.1 lbs.

Sample	Energy Level	Energy	Height	Thickness
WR/PE-1	1000	150	9.9	0.15
WR/PE-2	1500	225	14.9	0.15
WR/PE-3	2000	300	19.9	0.15
WR/VE-1	1000	160	10.6	0.16
WR/VE-2	1500	240	15.9	0.16
WR/VE-3	2000	320	21.2	0.16
BR/PE-1	1000	140	9.3	0.14
BR/PE-2	1500	210	13.9	0.14
BR/PE-3	2000	280	18.5	0.14
BR/VE-5	1000	140	9.3	0.14
BR/VE-3	1500	210	13.9	0.14
BR/VE-4	2000	280	18.5	0.14
GK/PE-1	1000	120	7.9	0.12
GK/PE-2	1500	180	11.9	0.12
GK/PE-3	2000	240	15.9	0.12
GK/VE-1	1000	120	7.9	0.12
GK/VE-2	1500	180	11.9	0.12
GK/VE-3	2000	240	15.9	0.12

TABLE 4. Impact energy level (in.lbs./in.), energy (in.lbs.), drop height (in.), and panel thickness (in.) for the impacts with the 1 in. diameter tup. The drop weight was 15.4 lbs.

Sample	Energy Level	Energy	Height	Thickness
WR/PE-4	1500	225	14.6	0.15
WR/PE-5	2500	375	24.4	0.15
WR/PE-6	3500	525	34.1	0.15
WR/VE-4	1500	240	15.6	0.16
WR/VE-5	2500	400	26.0	0.16
WR/VE-6	3500	560	36.4	0.16
BR/PE-4	1500	210	13.6	0.14
BR/PE-5	2500	350	22.7	0.14
BR/PE-6	3500	490	31.8	0.14
BR/VE-6	1500	210	13.6	0.14
BR/VE-7	2500	350	22.7	0.14
BR/VE-8	3500	490	31.8	0.14
GK/PE-4	1500	180	11.7	0.12
GK/PE-6	2500	300	19.5	0.12
GK/PR-8	3500	420	27.3	0.12
GK/VE-4	1500	180	11.7	0.12
GK/VE-5	2500	300	19.5	0.12
GK/VE-6	3500	420	27.3	0.12

Table 5 - The fraction of total impact energy stored elastically during the impact event, (Emax-Emin)/(Emax), for all 36 impact tests performed in this study.

IMPACT ENERGY (IN-LB/IN THICKNESS) / COMPOSITE SPECIMEN	E-GLASS BIAXIAL REINFORCED POLYESTER	E-GLASS BIAXIAL REINFORCED VINYL ESTER	E GLASS/KEVLAR HYBRID WEAVE POLYESTER	E GLASS/KEVLAR HYBRID WEAVE VINYL ESTER	E-GLASS WOVEN ROVING POLYESTER	E-GLASS WOVEN ROVING VINYL ESTER
1000 (0.5 IN DIA TUP) (1.0 IN DIA TUP)	0.791 --	0.791 --	0.579 --	0.570 --	0.688 --	0.474 --
1500 (0.5 IN DIA TUP) (1.0 IN DIA TUP)	0.766 0.674	0.671 0.687	0.319 0.502	0.323 0.474	0.390 0.442	0.362 0.452
2000 (0.5 IN DIA TUP) (1.0 IN DIA TUP)	0.626 --	0.502 --	0.131 --	0.149 --	0.211 --	0.142 --
2500 (0.5 IN DIA TUP) (1.0 IN DIA TUP)	-- 0.664	-- 0.609	-- 0.281	-- 0.206	-- 0.165	-- 0.254
3500 (0.5 IN DIA TUP) (1.0 IN DIA TUP)	-- 0.620	-- 0.403	-- 0.146	-- 0.119	-- 0.225	-- 0.214

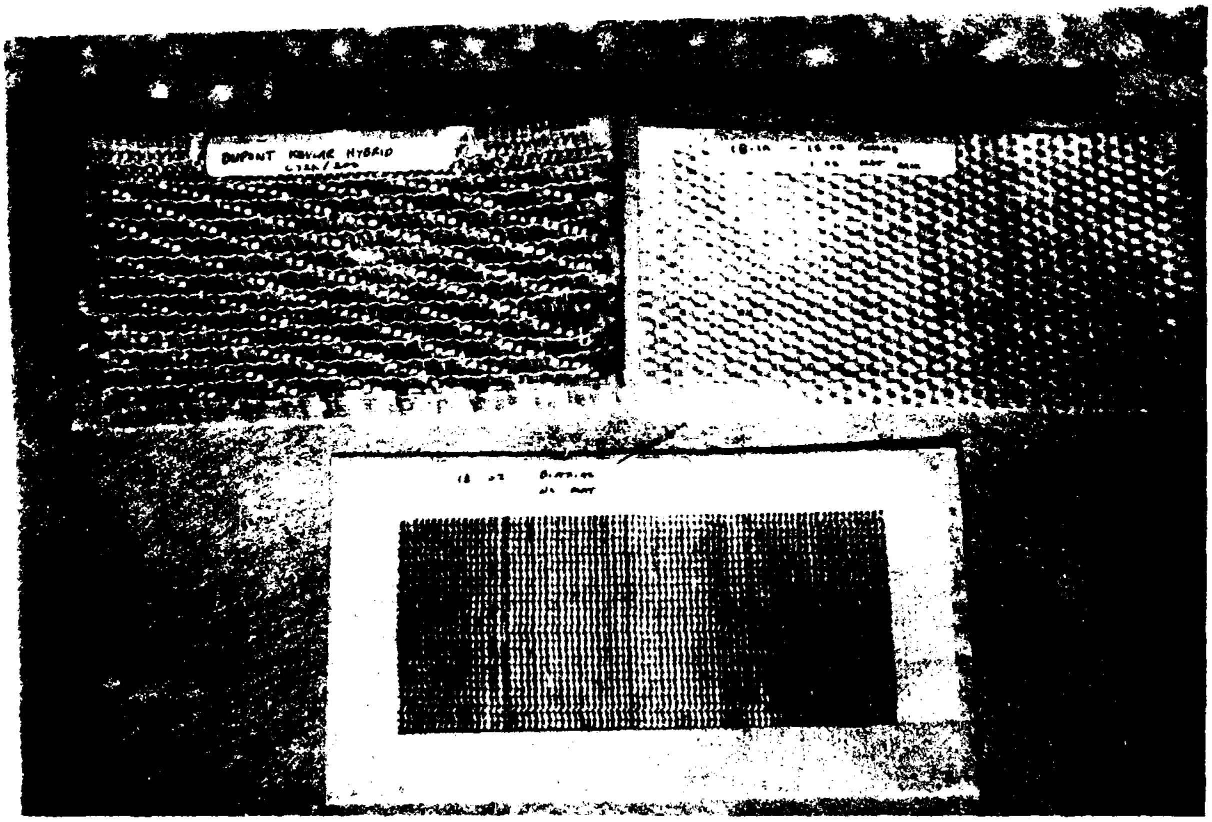


Fig. 1 - The reinforcements used in this study. Glass/Kevlar Hybrid (upper left), woven roving (upper right), and biaxial reinforcement.

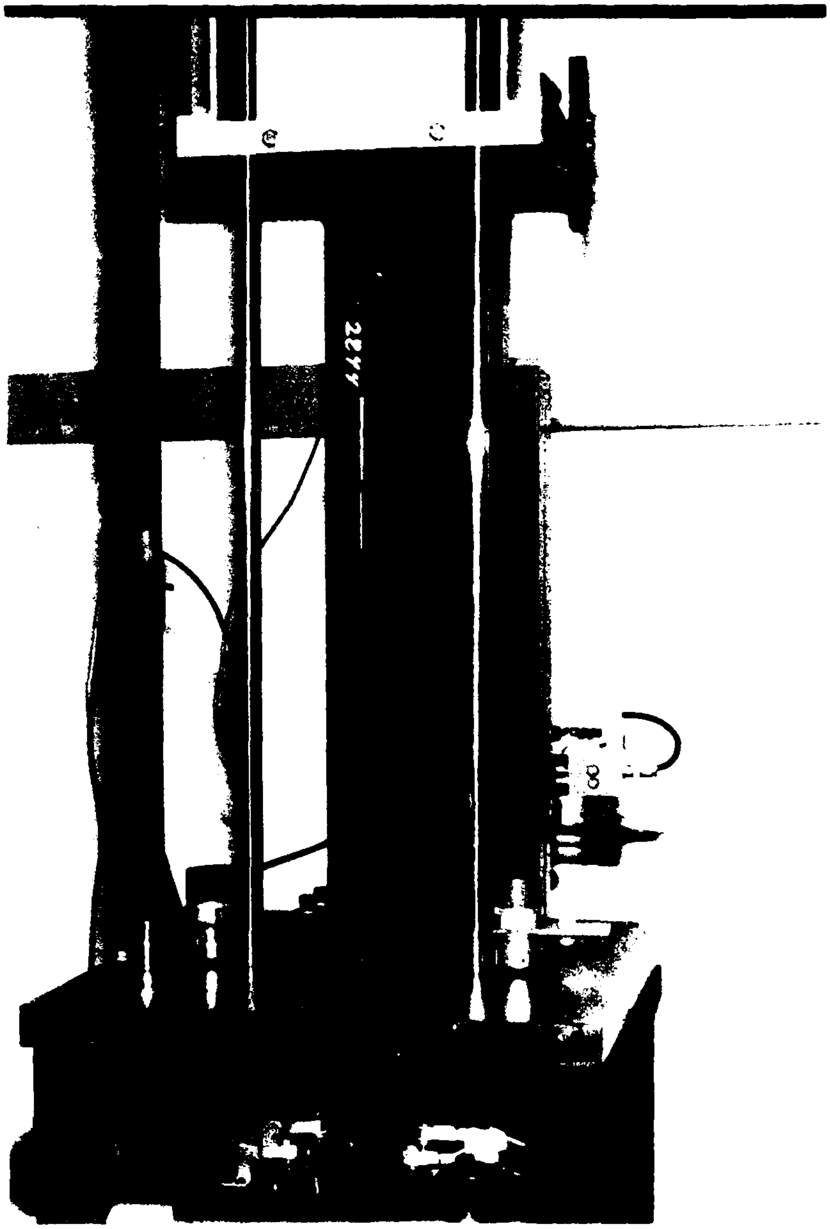


Fig. 2 - The Dynatup Model 8200 drop tower fitted with the 1 inch diameter tup.

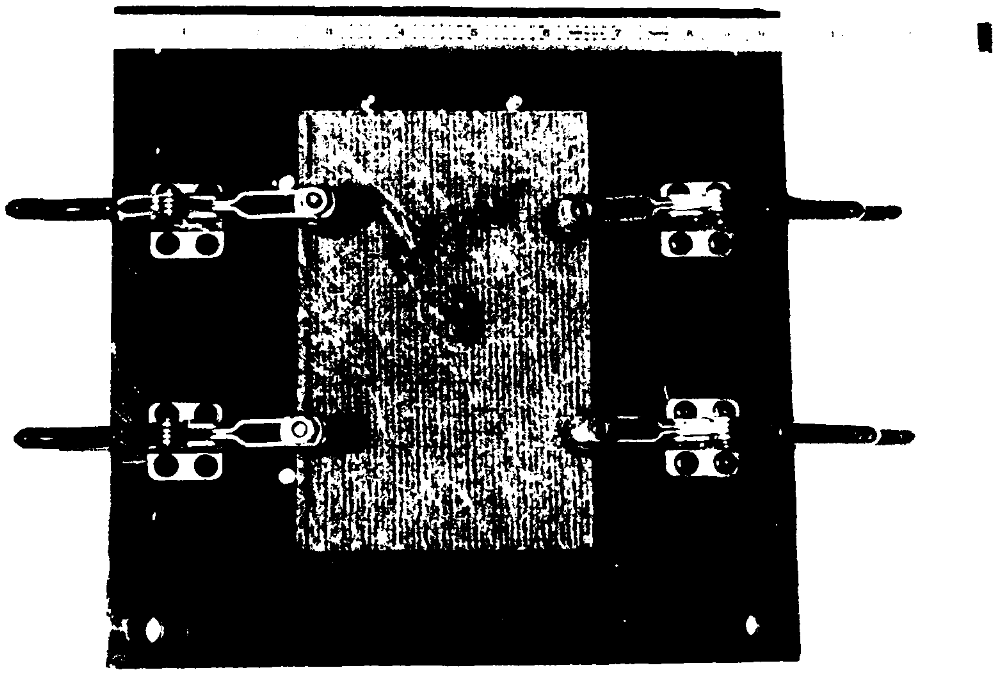


Fig. 3 - The Boeing Model 7260 support fixture with a sample in place. The panel is centered with alignment pins located at the top and and left panel edges.

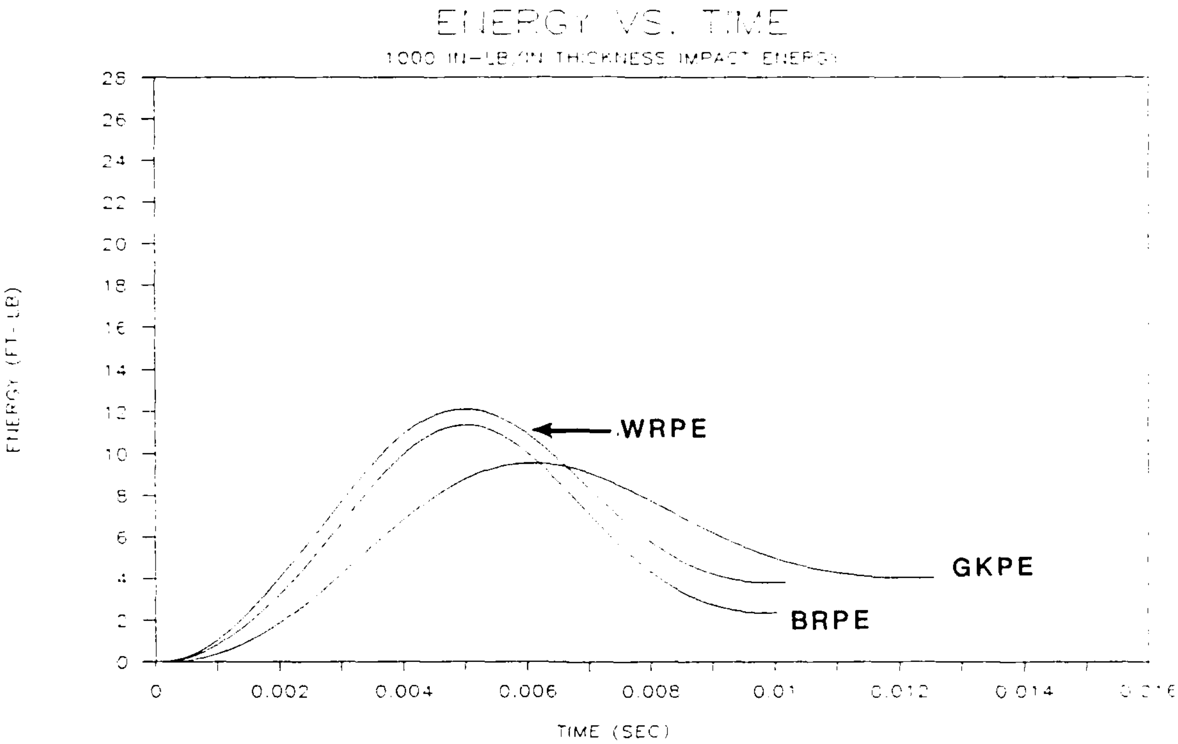


Fig. 4 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 1000 in. lbs./in. with the 0.5 in. diameter tup

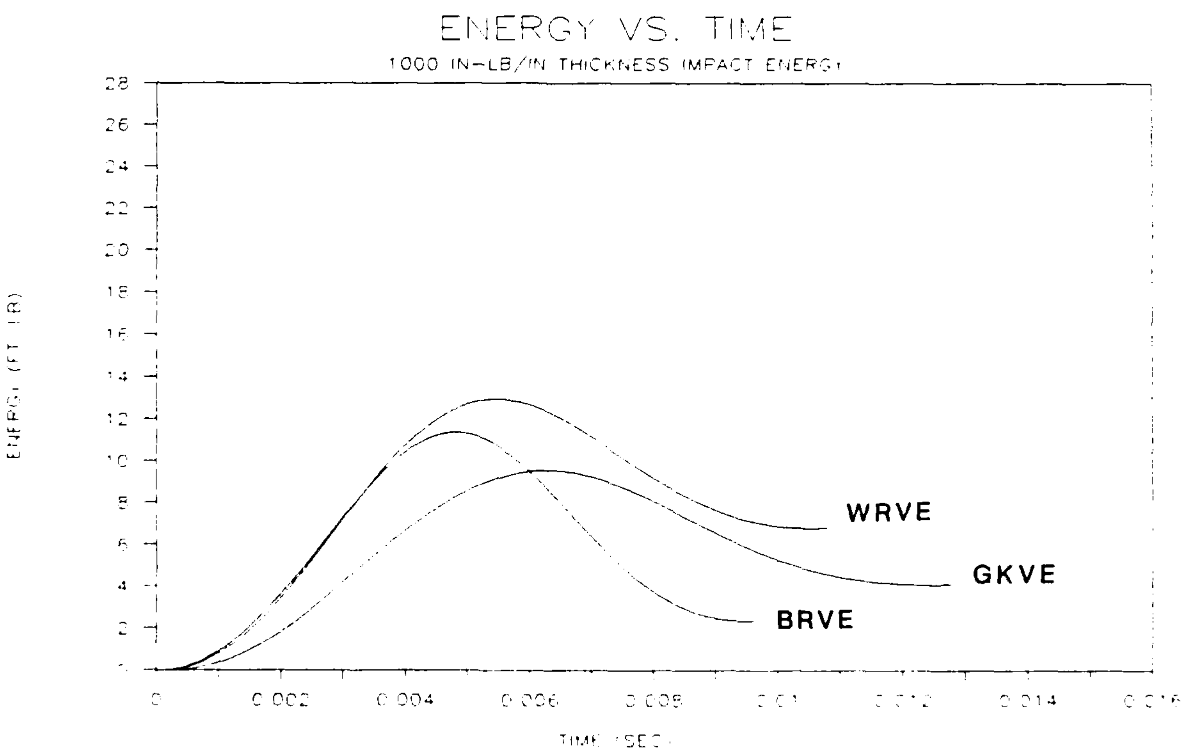


Fig. 5 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 1000 in. lbs./in. with the 0.5 in. diameter tup

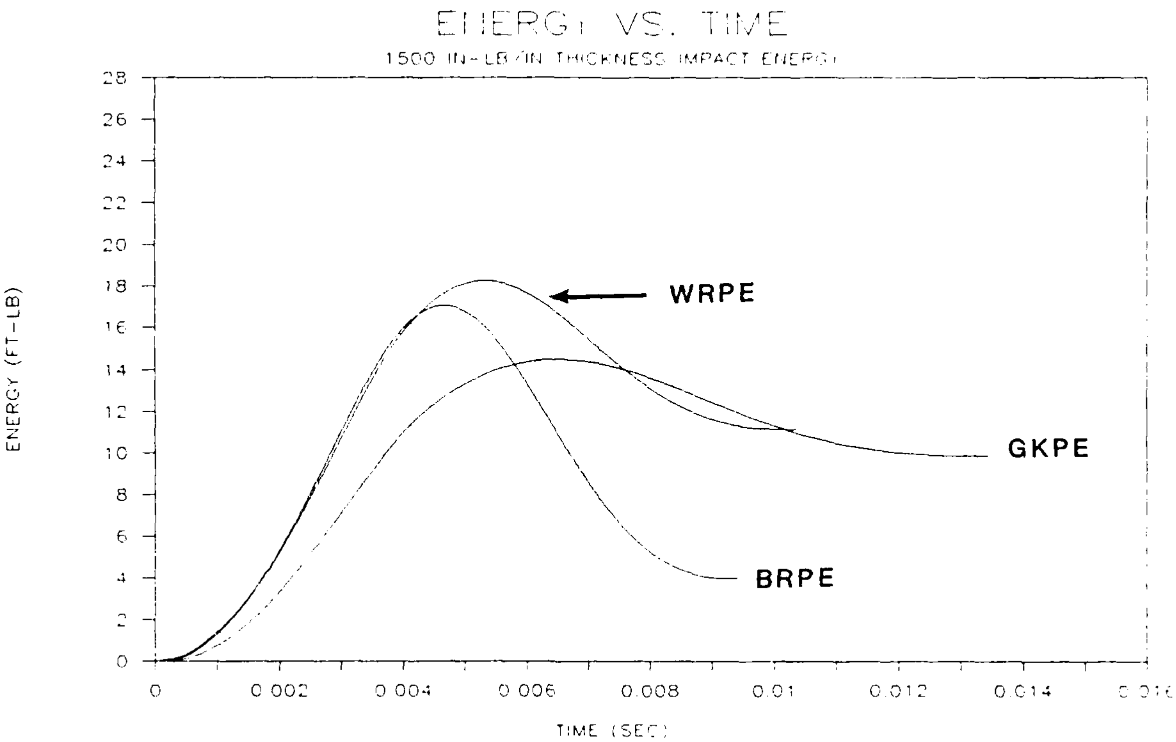


Fig. 6 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 1500 in. lbs./in. with the 0.5 in. diameter tup

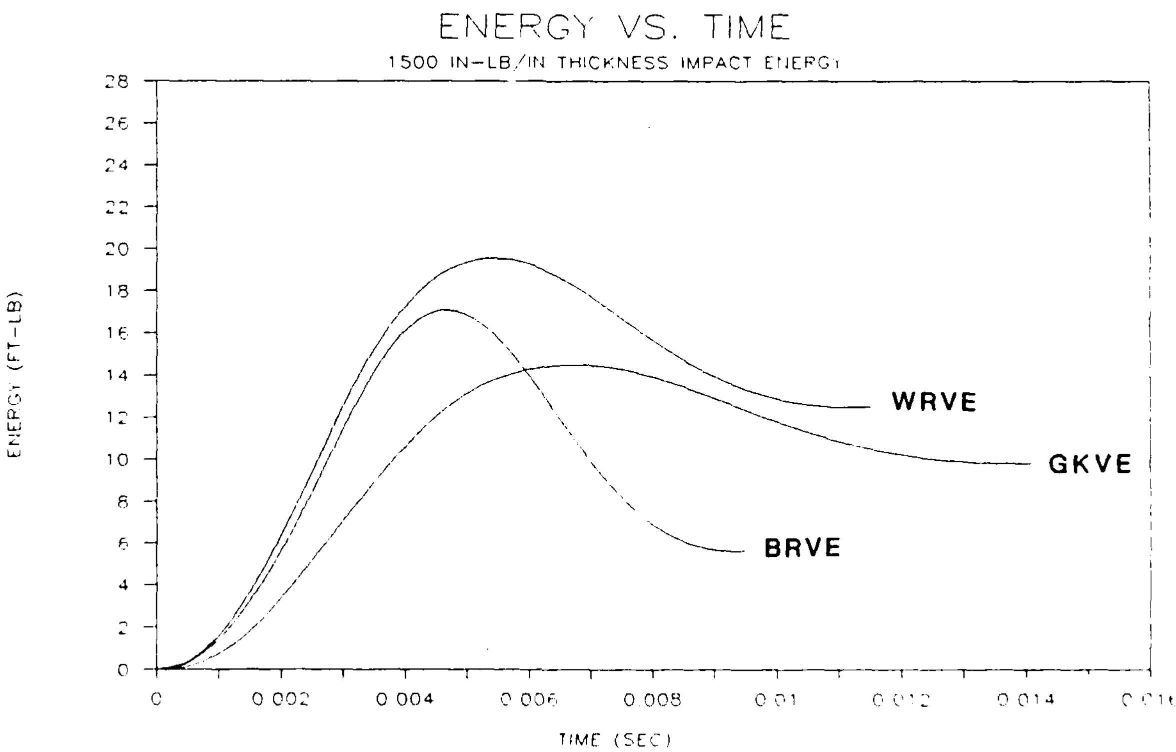


Fig. 7 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 1500 in. lbs./in. with the 0.5 in. diameter tup

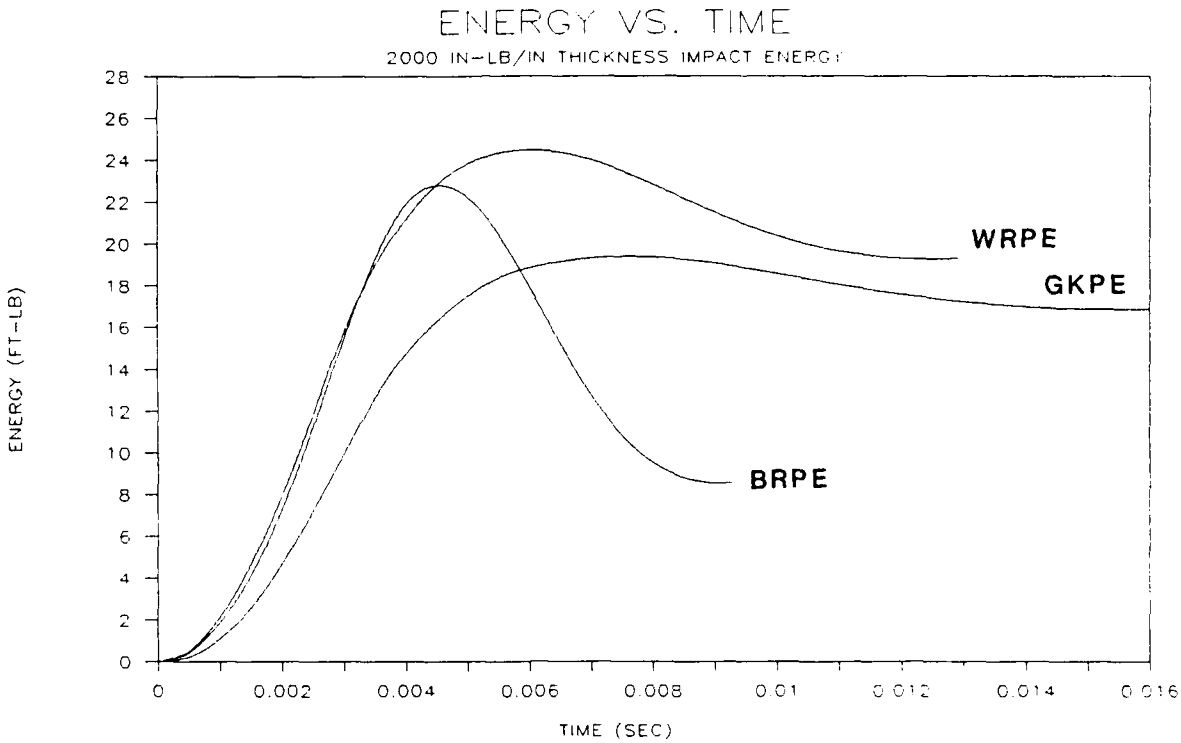


Fig. 8 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 2000 in. lbs./in. with the 0.5 in. diameter tup

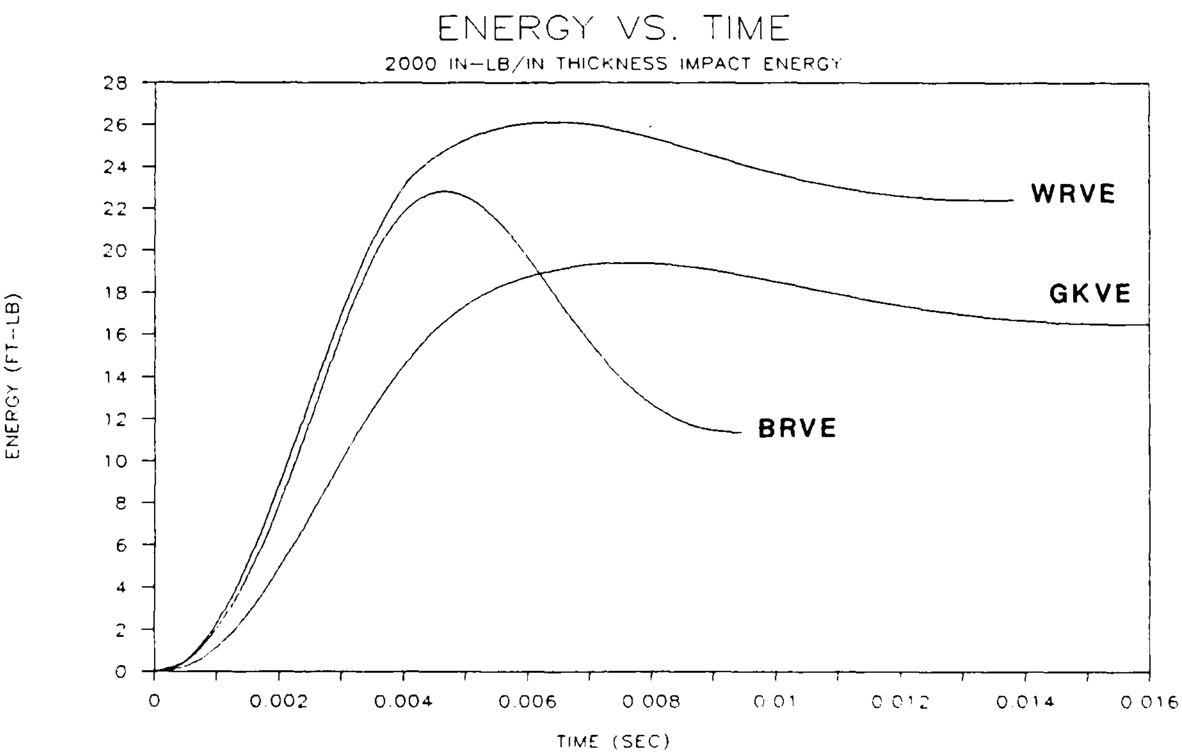


Fig. 9 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 2000 in. lbs./in. with the 0.5 in. diameter tup

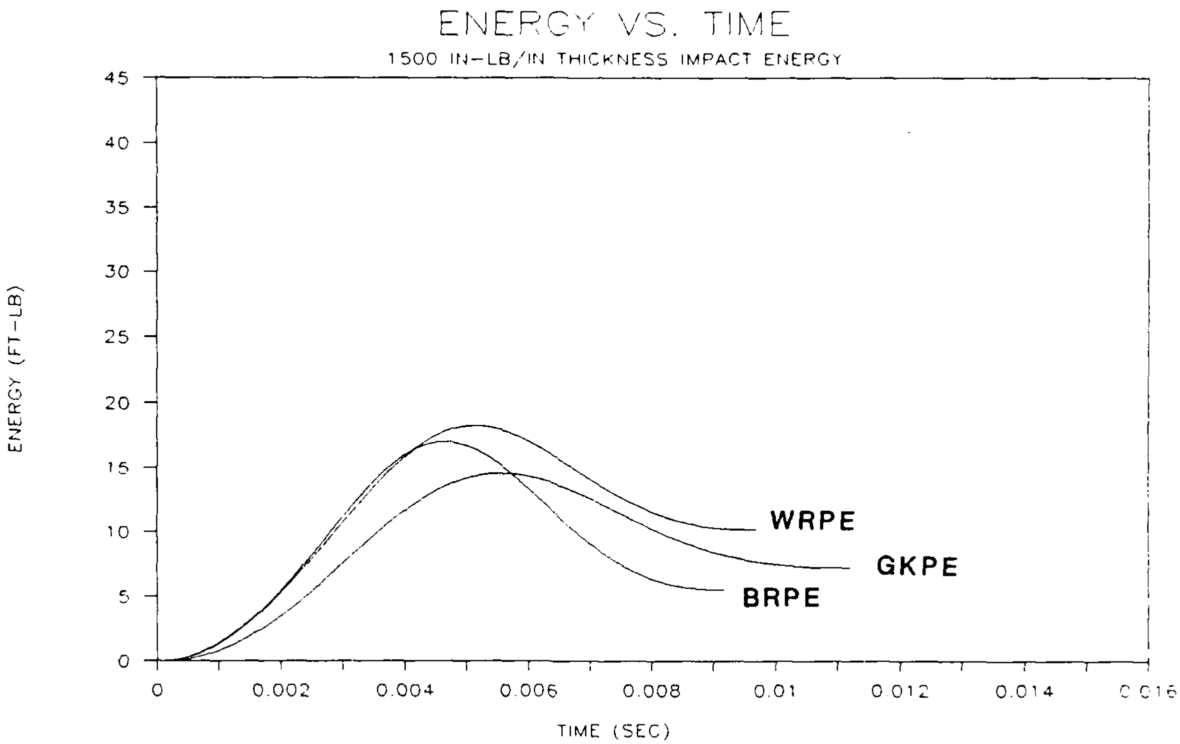


Fig. 10 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 1500 in. lbs./in. with the 1.0 in. diameter tup

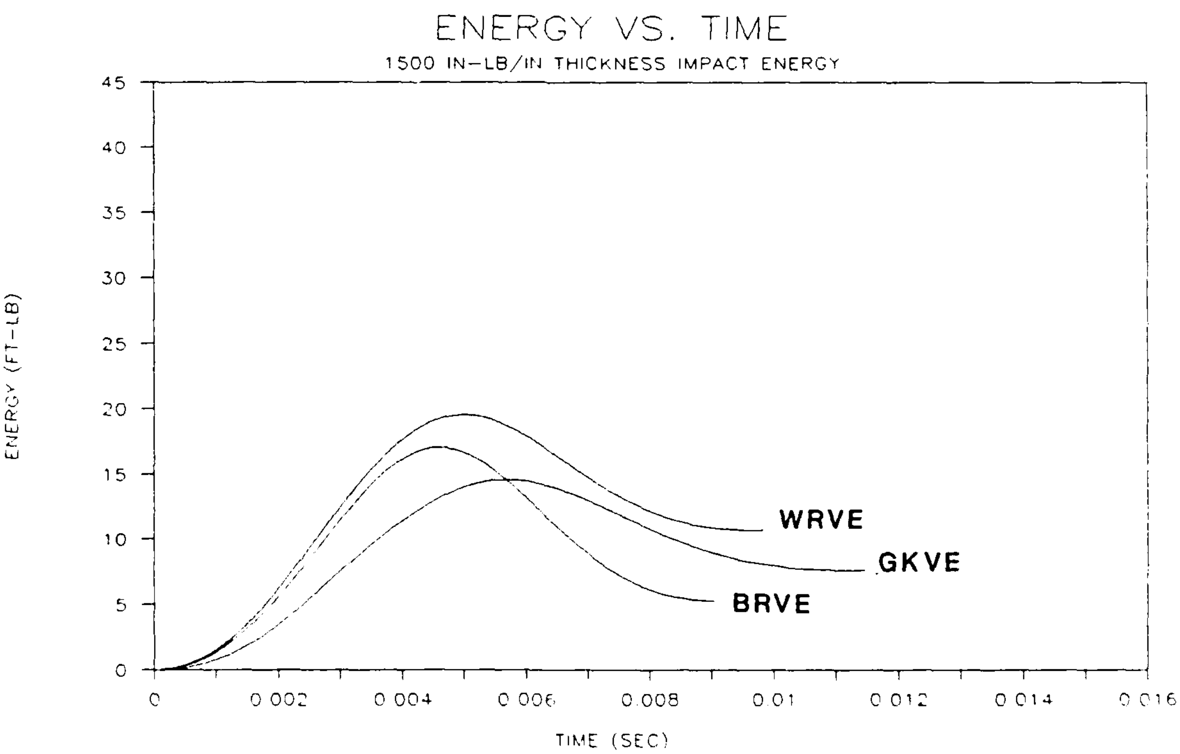


Fig. 11 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 1500 in. lbs./in. with the 1.0 in. diameter tup

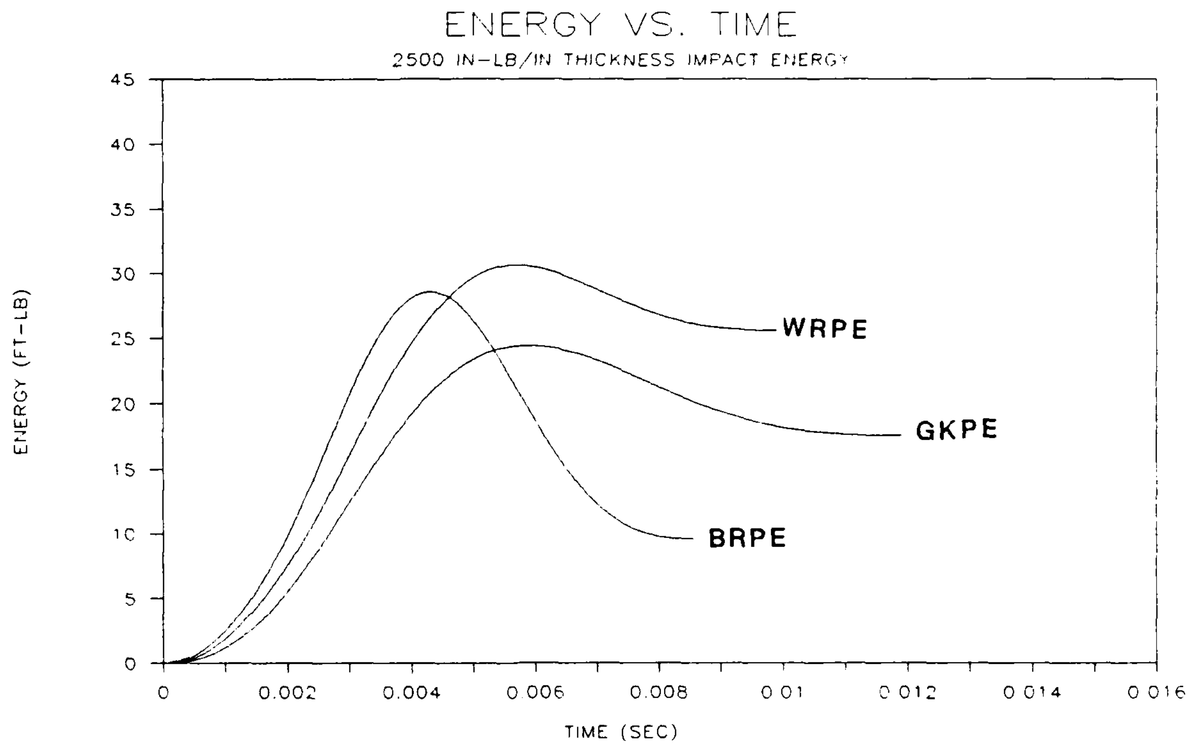


Fig. 12 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 2500 in. lbs./in. with the 1.0 in. diameter tup

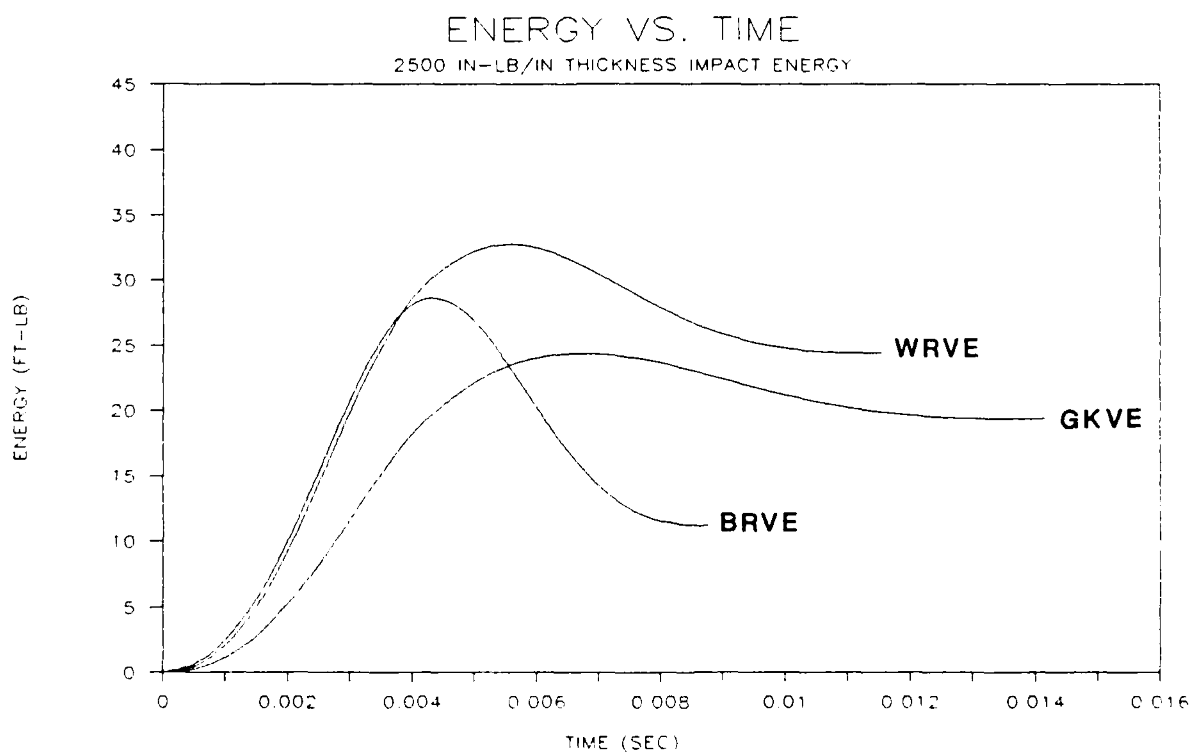


Fig. 13 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 2500 in. lbs./in. with the 1.0 in. diameter tup

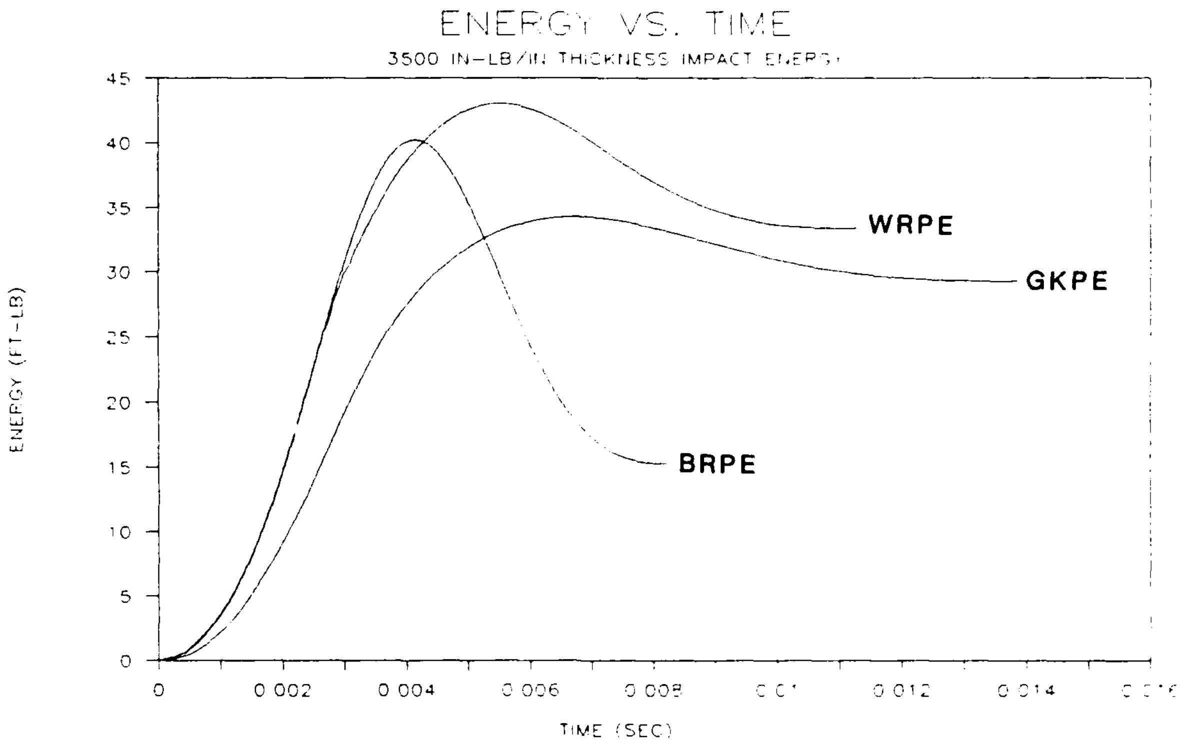


Fig. 14 Energy-time curves for WR/PE, BR/PE, and GK/PE impacted at 3500 in. lbs./in. with the 1.0 in. diameter tup

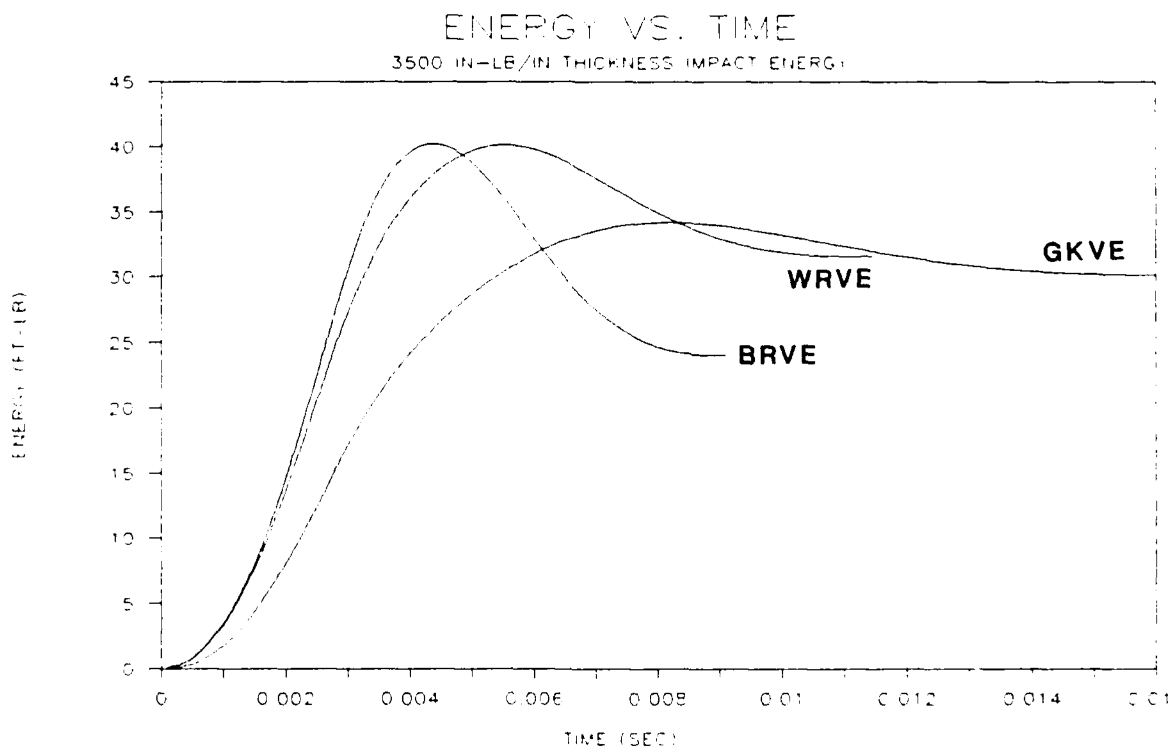


Fig. 15 Energy-time curves for WR/VE, BR/VE, and GK/VE impacted at 3500 in. lbs./in. with the 1.0 in. diameter tup

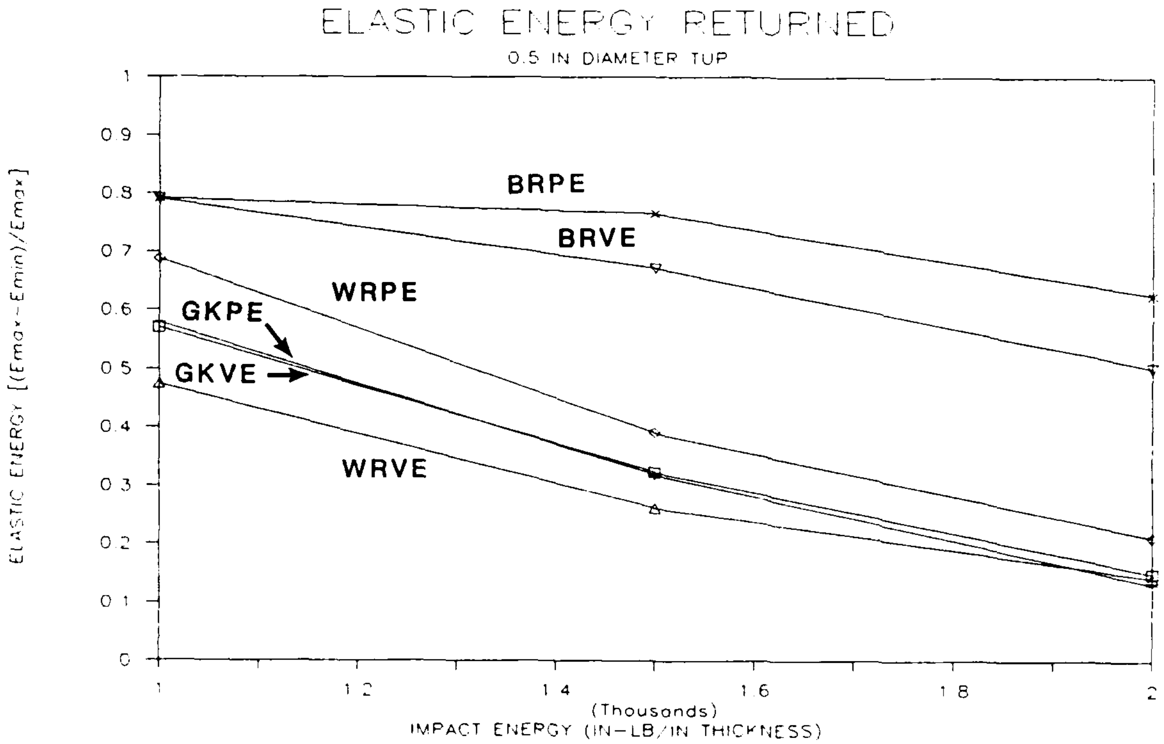


Fig. 16 Stored elastic energy (Emax-Emin)/(Emax) vs. impact energy level for the 0.5 in. diameter tup impacts

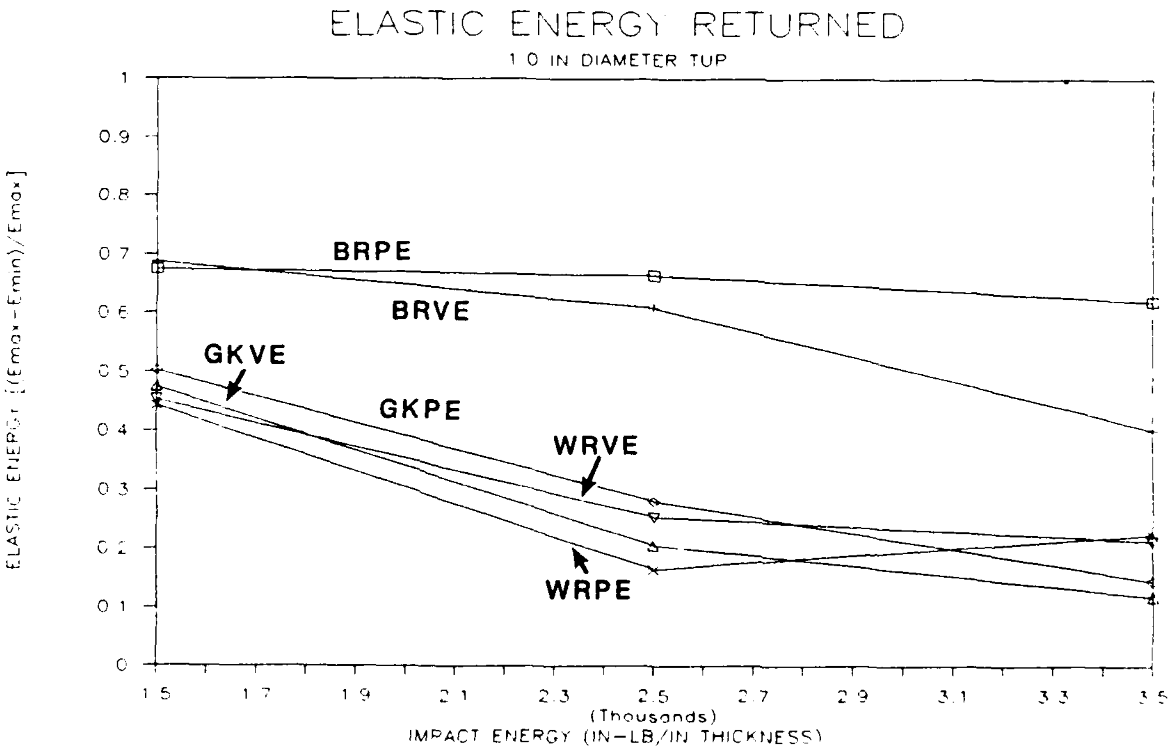


Fig. 17 Stored elastic energy (Emax-Emin)/(Emax) vs. imapct energy level for the 1.0 in. diameter tup impacts

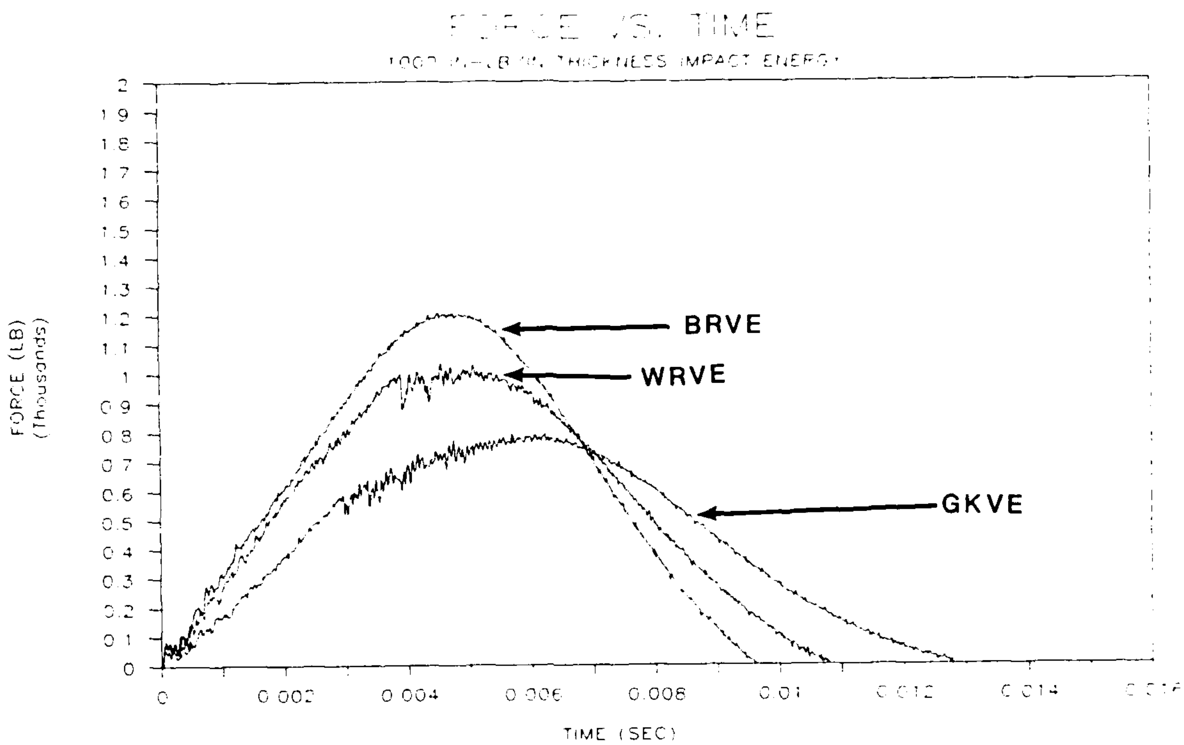


Fig. 18 Force-time curves for WR/VE, BR/VE, and GK/VE impacted at 1000 in. lbs./in. with the 0.5 in. diameter tup

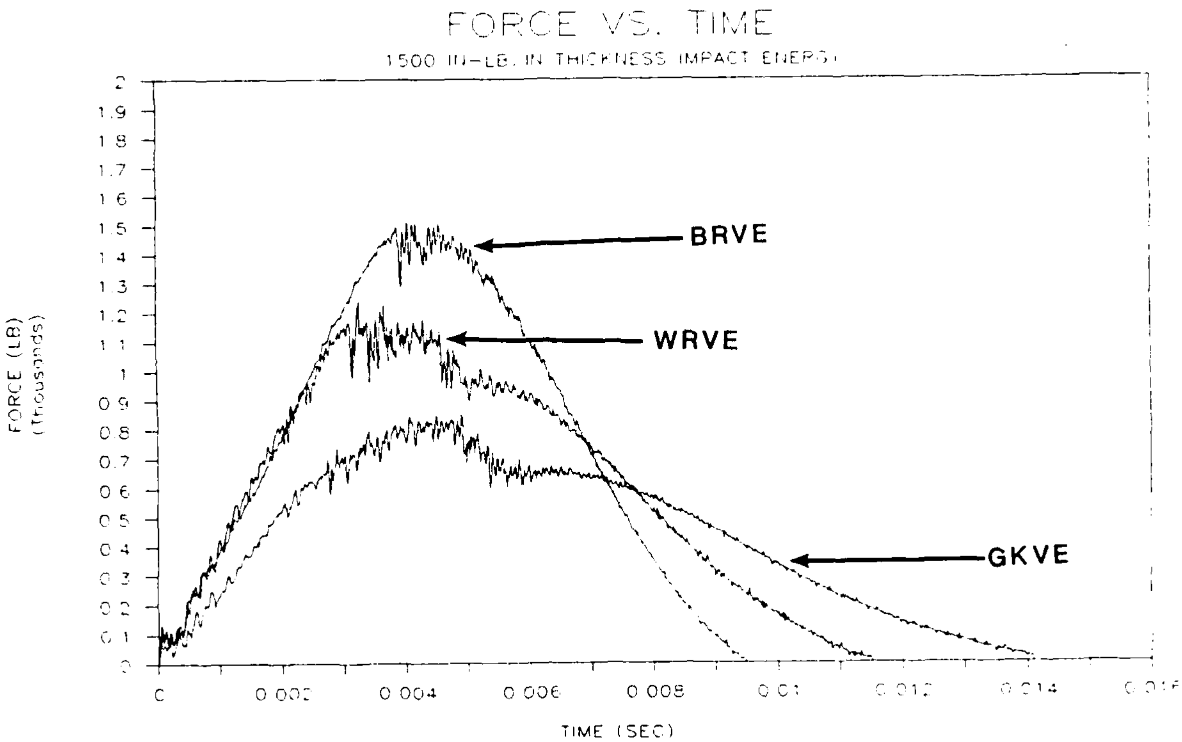


Fig. 19 Force-time curves for WR/VE, BR/VE, and GK/VE impacted at 2000 in. lbs./in. with the 0.5 in. diameter tup

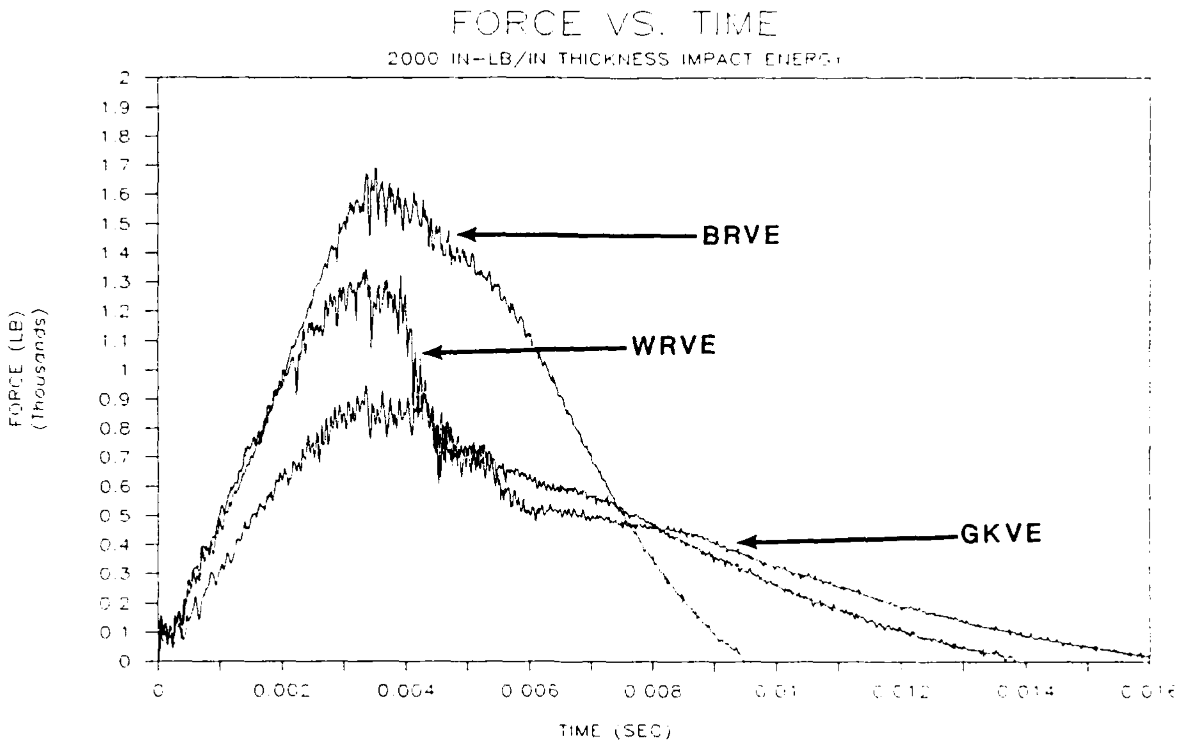


Fig. 20 Force-time curves for WR/VE, BR/VE, and GK/VE impacted at 2000 in. lbs./in. with the 0.5 in. diameter tup

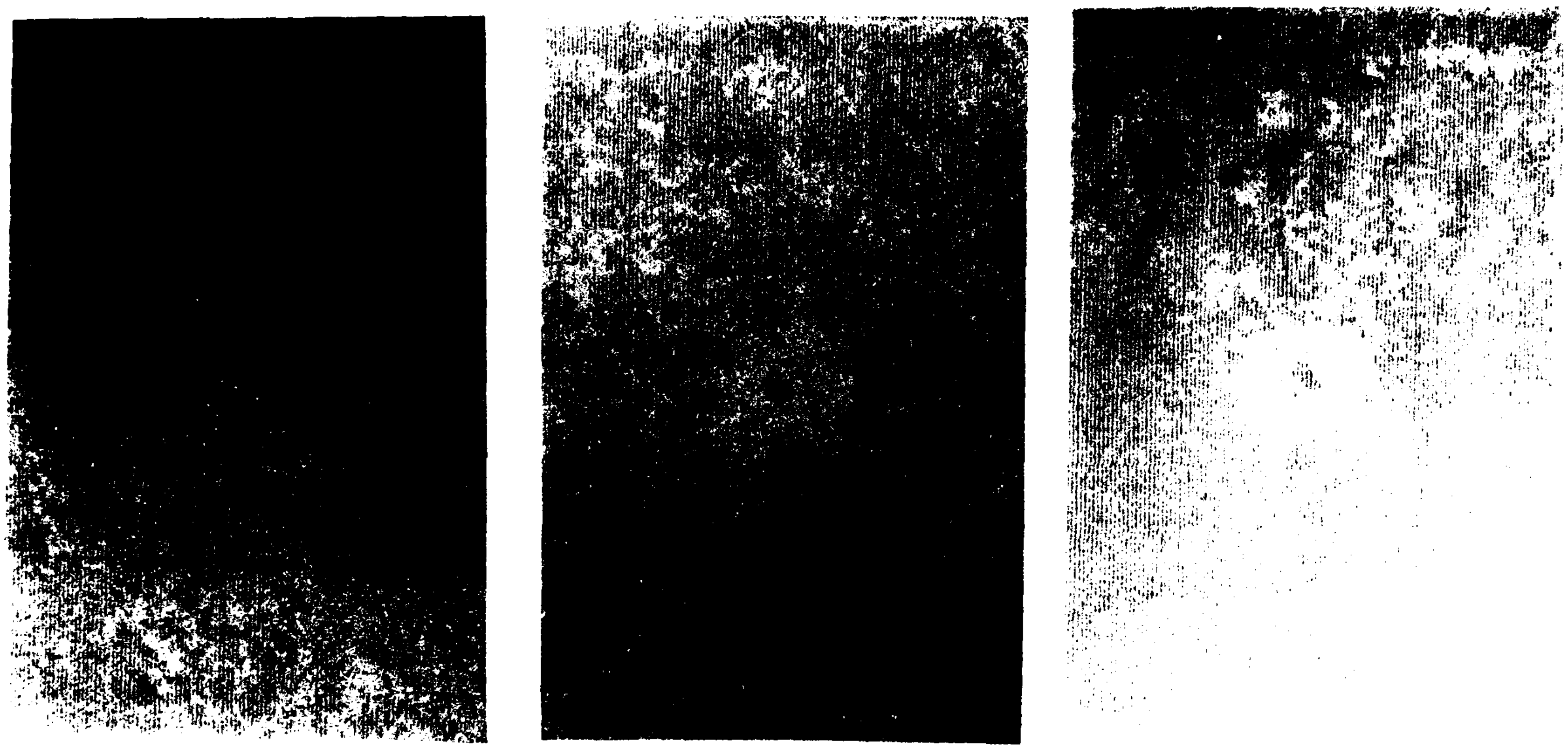


Fig. 21 - Ultrasonic C-scans of WR/VE impacted with the 1.0 inch diameter tup at (from left to right) 1500, 2500, and 3500 in. lbs./in.

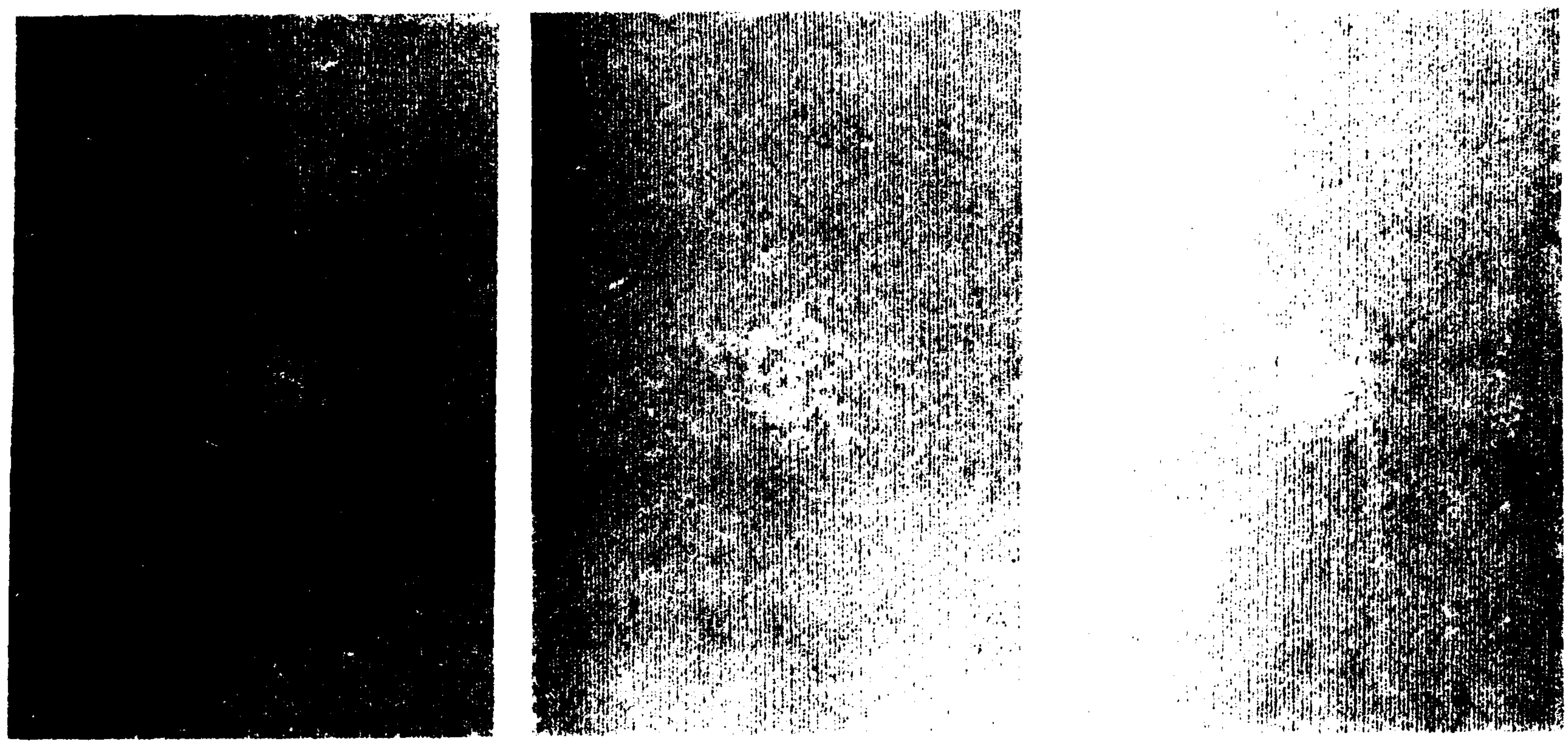


Fig. 22 - Ultrasonic C-scans of BR/VE impacted with the 1.0 inch diameter tup at (from left to right) 1500, 2500, and 3500 in. lbs./in.

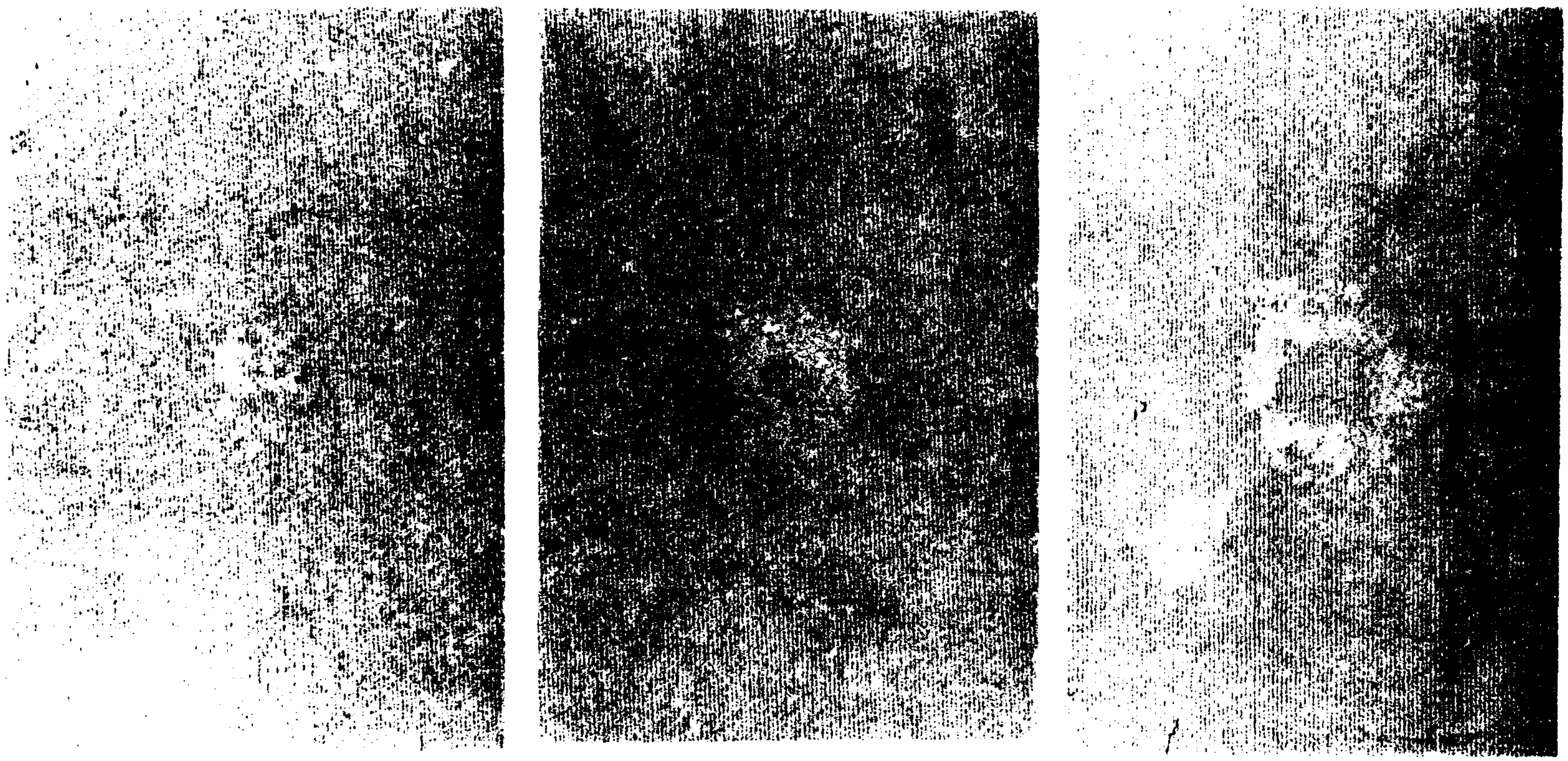
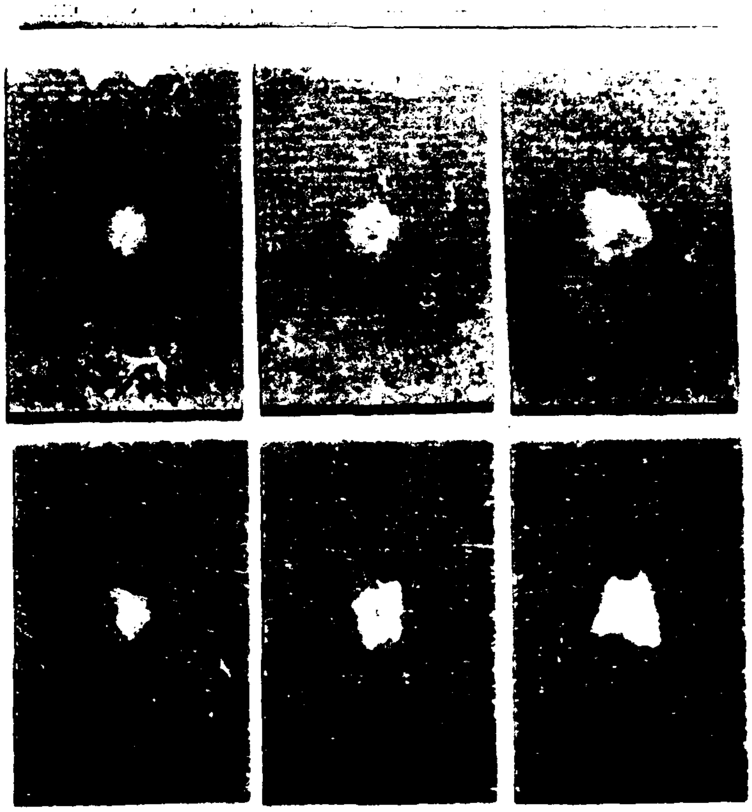


Fig. 23 - Ultrasonic C-scans of GK/VE impacted with the 1.0 inch diameter tup at (from left to right) 1500, 2500, and 3500 in. lbs./in.



1000 1500 2000

Fig. 24 - Backface damage of WR/PE (above) and WR/VE impacted with the 0.5 inch diameter tup at 1000, 1500, and 2000 in. lbs./in.

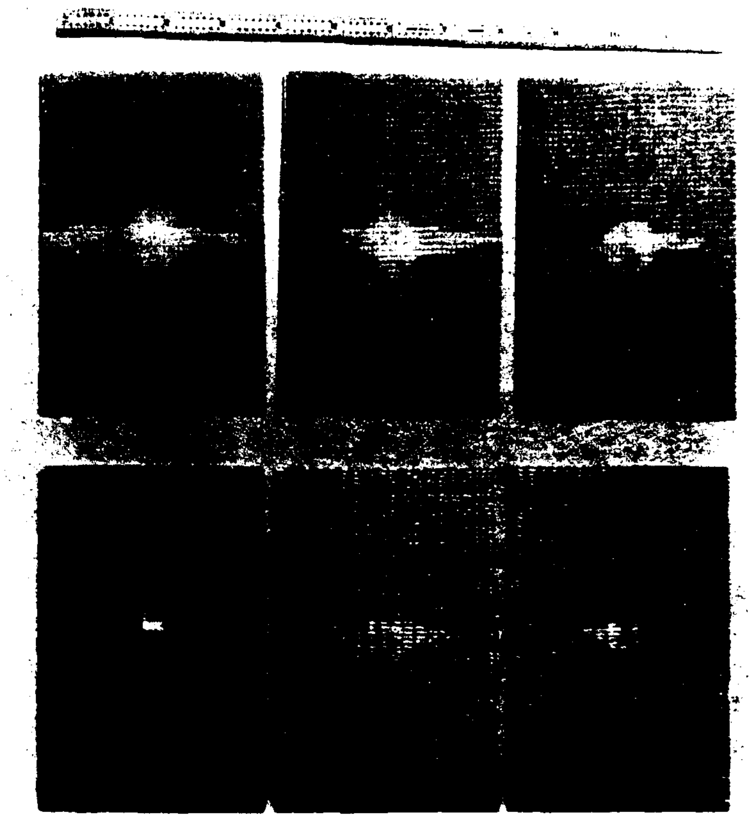


Fig. 25 - Backface damage of BR/PE (above) and BR/VE impacted with the 0.5 inch diameter tup at 1000, 1500, and 2000 in. lbs./in.

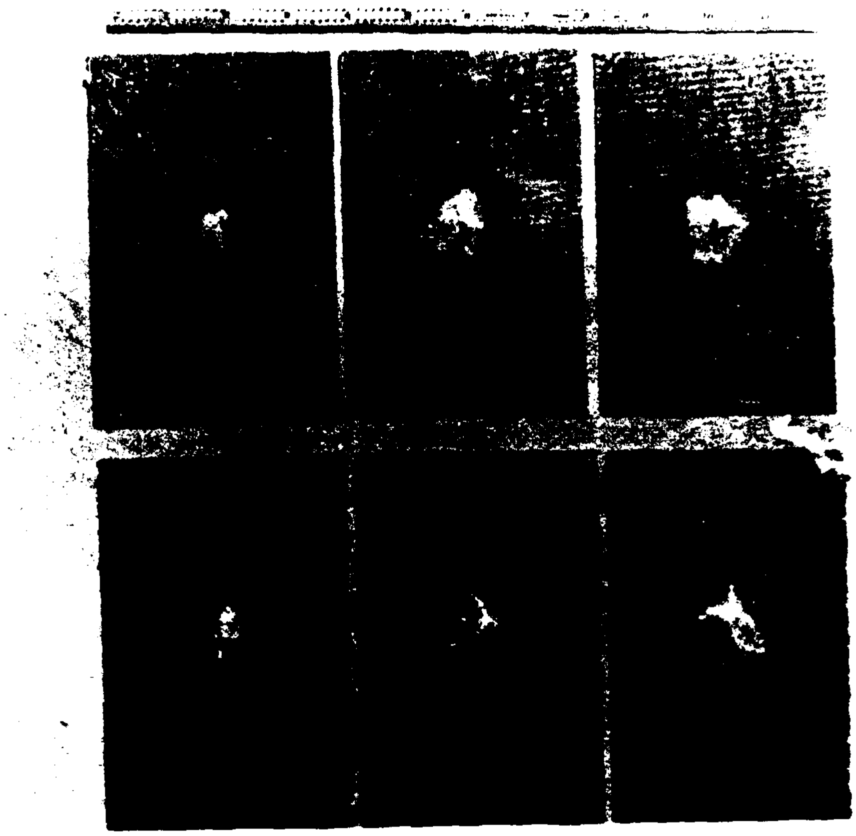


Fig. 26 - Backface damage of GK/PE (above) and GK/VE impacted with the 0.5 inch diameter tup at 1000, 1500, and 2000 in. lbs./in.

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